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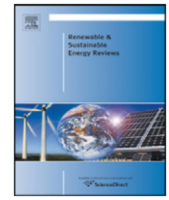

A review of agricultural crop residue supply in Canada for cellulosic ethanol production

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ABSTRACT

This paper estimates the availability of agricultural crop residue feedstocks in Canada for cellulosic ethanol production. Canada's major field crops generate 100.6 million dry mega grams (Mg) of crops per year while non-forage crops produce 67 million dry Mg, leaving abundant agricultural residues for use as second generation feedstock for cellulosic ethanol production. This study used crop production and livestock data from Statistics Canada for a 10-year period (2001–2010), as well as tillage data from Statistics Canada census years 2001 and 2006, to estimate crop residue availability by province and soil zone. Total residue yield from crops is calculated by incorporating straw to grain ratios. Total agricultural residues available for ethanol production are computed by deducting soil conservation and livestock uses. An average of 48 million dry Mg of agricultural residues is available per year, with a minimum of 24.5 million dry Mg in drought year 2002. This implies an average yearly potential ethanol production of 13 billion litres from crop residues over the 2001–2010 period, with a minimum of 6.6 billion litres in 2002. Ontario, Manitoba, Saskatchewan, and Quebec have enough agricultural residue supply to set up ethanol plants using agricultural crop residues as primary lignocellulosic feedstocks. There is great variability in agricultural residue production between the provinces and by soil zone. Understanding variability in feedstock supply is important for the economics and operational planning of a cellulosic ethanol biorefinery. Factors such as residue yield per hectare and soil zone will influence cellulosic ethanol plant establishment in order to exploit the abundance of lignocellulosic biomass for an ethanol plant.

Contents

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1. Introduction

The demand for lignocellulosic ethanol is increasing in many countries. Ethanol made from renewable biomass not only provides a clean and sustainable energy alternative to fossil fuel [1], but also addresses some of the emerging issues related to first-generation biofuel conversion technologies that use food crops as feedstocks for biofuel production. Numerous studies have provided empirical results suggesting significant increases in international market prices of cereal and oilseed crops due to the growth of crop-based biofuels [2–4]. Concerns are mounting over the impact of first-generation crop-based biofuels on food security of millions of people across the world, leading to increased demands for ethanol derived from second-generation conversion technologies based on lignocellulosic feedstocks such as woody biomass, agricultural residues, dedicated energy crops, and municipal waste.

In Canada, agricultural crop residues represent an abundant lignocellulosic biomass resource for ethanol production. Currently, this type of feedstock is not commercially utilized in spite of its abundance. Crops are grown on 36 million hectares of land [5], representing 53% of total farmland. This generates millions of tonnes of lignocellulosic crop residues annually. Biomass supply for Canada and US has been reported in a number of publications [6–10]. Sokhansanj et al. [11] estimated average net yield and quantities of straw available in Canadian Prairies at 15 million mega grams (Mg) from 1994 to 2003, after deductions for soil conservation and livestock use. Their estimates used data on land area, yield, and total grain production for four cereal crops (wheat, barley, oats, and flax) over the 10-year period (1994–2003). Estimates of available agricultural residues in Canada vary between studies, partly explained by differences in breadth, depth, and approach used in the analysis. Wood and Layzell [10] reported that approximately 56 million oven-dry Mg of straw/stover were produced from crops in Canada, leaving approximately 17 million oven-dry Mg as lignocellulosic feedstock for bioenergy, after deducting soil surface coverage and livestock use. Kumarappan et al. [8] reported availability of 42 million dry Mg, using average crop yield data for barley, oats, corn, and wheat for the years 1999–2003. Mabee et al. [12] estimated 9–19 million Mg agricultural residues, noting that this would potentially yield 1.3–9 billion litres of ethanol per year. Estimates of Canadian agricultural residue availability from cereal crops have ranged from 2.7 to 18 million dry Mg per annum. Agriculture and Agri-Food Canada (AAFC) has developed a web-based tool called Biomass Inventory Mapping and Analysis Tool (BIMAT) [13] whose biomass inventory data can be queried to obtain amounts of agricultural residues for selected crops in certain locations of Canada. However, yearly variation, summary of biomass supply in each province, and some crop biomass are not yet available in this system.

Although the Canadian ethanol industry is substantially smaller than the U.S. industry, ethanol production capacity is increasing significantly [14]. Canadian annual ethanol production reached 1.9 billion litres in 2010 compared to merely 8000 l in 1980 [15]. Canada's ethanol production is mainly derived from two first-generation feedstocks: corn (Eastern Canada) and wheat grain (Western Canada). Like other countries, Canada has become interested in second-generation conversion technologies that use lignocellulosic feedstocks to produce ethanol in a sustainable way. AAFC's Agricultural Bioproducts Innovation Program (ABIP) established the Cellulosic Biofuels Network to initiate research and development aimed at eliminating constraints to the Canadian ethanol industry and providing Canada with a low-cost economic and environmental plan for ethanol production based on sustainable use of food-crop residues, dedicated biomass crops, and marginal lands. Biomass supply represents a significant component of the sustainability of this industry. Therefore, it is useful to provide ongoing understanding of biomass supply needs including updates of yearly variation in order to meet technoeconomic and business strategies for cellulosic biofuel development in Canada. The overall objective of this paper is to provide new estimates of lignocellulosic biomass availability from Canadian agricultural crop residues for the period 2001–2010. The paper quantifies potential cellulosic ethanol production capacity and variation by region, including identifying constraints to sustainable supply of lignocellulosic feedstock from major agricultural residues. This study also presents a detailed case study of agricultural crop residue supply by soil zone using Saskatchewan as the baseline. Analysing biomass supply by soil zone represents a much lower level of data disaggregation and may be useful in characterizing the relative abundance of biomass by location. This factor is especially relevant for low bulk density feedstocks such as straw, an attribute that may constrain biomass markets to be regional in nature due to logistical and transportation costs associated with low bulk density feedstocks.

2. Crop production and distribution in Canada

In order to estimate agricultural crop residue supply, this study uses Statistics Canada crop production data [16] for ten major field crops grown in Canada over a 10-year period (2001–2010), as summarized in Fig. 1. These ten field crops produce an average of 100.6 million dry Mg of output each year. Tame hay has the highest output, exceeding wheat over the 10-year period. Canada produces about 25.8 million dry Mg of tame hay each year, broadly distributed from Eastern Canada to Western Canada. Wheat is the dominant crop in Western Canada while corn dominates in Eastern Canada, producing an average of 23.8 and 12.5 8 million dry Mg per year, respectively. In terms of data definition, 'all wheat' includes winter wheat, spring wheat, and durum wheat; 'all corn for grain' includes corn for grain and genetically modified corn for grain; 'all soybeans' is the sum of soybean and genetically modified soybean. Saskatchewan, Alberta, Ontario, Manitoba, and Quebec together produce 96% of Canadian crops. Production in the remaining provinces (Nova Scotia, Prince Edward Island, New Brunswick, Newfoundland and Labrador, and British Columbia) accounts for only 4% of Canada's production. The distribution of field crops is different between Eastern Canada and Western Canada. Corn is the largest field crop in Eastern Canada, especially Ontario and Quebec which produce 62.6% and 34.1% of Canada's corn respectively. Fodder corn and soybeans are also mainly produced in Eastern Canada. Canadian Prairies (Alberta, Saskatchewan, and Manitoba in Western Canada) account for 82% of all crop lands in Canada [5], producing 62.4% of Canadian field crops. Wheat is Canada's largest crop in terms of both area seeded and production, with over 10

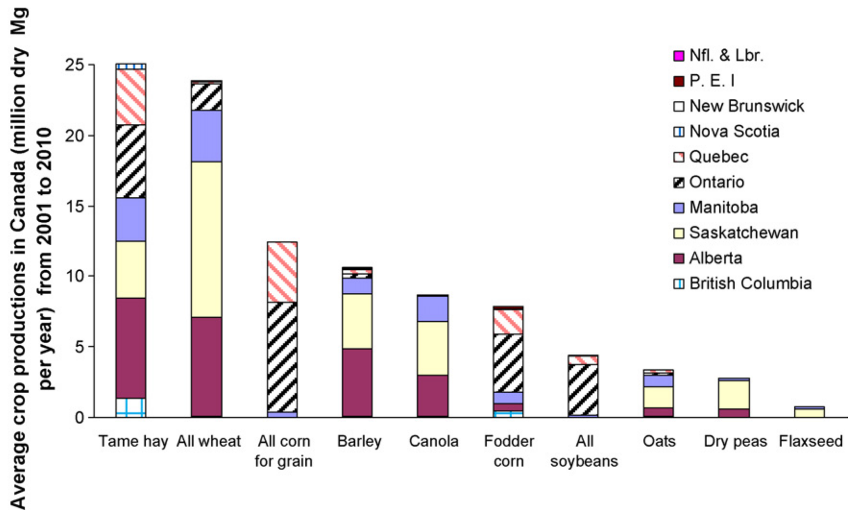

Fig. 1. Average annual production of top ten crops in Canada for 2001–2010.

million hectares. Approximately 92% of Canadian wheat is grown in the prairie provinces of Saskatchewan, Alberta, and Manitoba which account for an average of 48%, 28% and 16% of total production respectively. Ontario is the only significant wheat-producing province in Eastern Canada, accounting for about 7% of total wheat production over this period. Spring wheat accounts for approximately 95% of the production in Canada, with winter wheat and drum wheat comprising the remaining 5%. The remaining crops (barley, canola, oats, dry peas, and flaxseed) are also predominantly produced in the Canadian Prairies. The concentration of cereal production in the Canadian Prairies implies that this region will be the largest supplier of cereal straw and other agricultural crop residues as lignocellulosic biomass feedstock for cellulosic ethanol production. Therefore, depending on supply certainties, a majority of second generation cellulosic ethanol plants would be located in the three prairie provinces of Saskatchewan, Alberta, and Manitoba, with cereal straw as their main feedstock.

3. Estimation of available crop straw for ethanol conversion in Canada

3.1. Total agricultural crop residue estimation

There is no specific statistical information on Canadian biomass or residues from agricultural crops. Crop straw differs with variety, climate, and soil conditions, all of which contribute to variability in annual yield. Most researchers used straw/grain ratios to estimate straw production from crops [10,11]. Straw/grain ratios used in this paper are based on Canadian inventory data given in Table 1 [10,17].

Table 1
Straw/grain ratio for Canadian crops [10,17].

Crop	Straw/grain ratio
Spring wheat	1.6
Winter wheat	1.2
Durum wheat	1.66
Tame Hay	0
Barley	1
Canola	1
Oats	1.5 (1–2)
Dry peas	1
Fodder corn	0
Flax	1.2 (1–1.4)
Corn for grain	1
Soybean	1

Wheat and oats have relatively higher straw/grain ratios. Apart from grain and oilseed crops, forage crops such as tame hay and fodder corn could be considered as potential sources of residues. However, forage crops are mainly produced for animal feed. Products from tame hay and fodder corn are mixed with straw for animal feeding, bedding, and export. There is no precise information on straw available from forage crops. In fact, straw from forage crops is not regarded as waste material. Therefore, the availability of residues from tame hay and fodder corn for ethanol conversion will not be considered in this study.

Average annual residue yields from dominant crops are calculated and shown in Fig. 2. On average, about 82.4 million dry Mg of agricultural residues are produced in Canada each year, excluding tame hay and fodder corn. Wheat straw dominates agricultural residue production. Canadian Prairie provinces account for 92.6% of total wheat straw supply. The Canadian Prairies are also the main producer of barley, oats, canola, dry peas, and flaxseed residues. Residues from corn and soybean are mainly produced in Ontario and Quebec, accounting for 96.7% and 95.4% of total Canadian residues from corn stover and soybean straw respectively. Overall, Saskatchewan has the largest crop residue supply each year, followed by Alberta and Ontario.

3.2. Crop residue supply and soil conservation

In spite of the availability of approximately 82.4 million dry Mg of agricultural residues from Canadian crops, only a certain percentage can be removed from the land and used for ethanol production or other industrial processing. In order to prevent wind and water erosion, a percentage of crop straw must be left on the farm to form soil organic matter [18]. The potential impacts of crop residue removal on soil productivity [19], soil carbon [20,21], and soil properties and soil erosion [22] have been analyzed. The amount of crop residues left on the farm depends on soil texture and field slope [11]. Various methods have been used to estimate the amount of residue left on the ground. Stumborg and Townley-Smith [23] recommended that cereal residues of 0.75 Mg ha^{-1} are required for area coverage in no-till or reduced tillage systems and 1.5 Mg ha^{-1} for conventional tillage. In their calculation of crop residues from wheat, barley, oat, and flaxseed in the Canadian Prairies, Sokhansanj et al. [11] assumed that 1 Mg ha^{-1} of straw should be left on the land for soil conservation. Stumborg and Townley-Smith [23] also recommended determining crop residues as a function of field slope, namely, 0.8–1.1 Mg ha^{-1} for gentle slope

Table 2
Percentage of tillage land [26] and average residue coverage in Canada.

	2001 total area prepared for seeding (%)			2006 total area prepared for seeding (%)			Average residues coverage[a] (Mg ha^{-1})
	Conventional tillage	Conservation tillage	No-till	Conventional tillage	Conservation tillage	No-till	
Prince Edward Island (P.E.I)	76	22	2	78	19	3	1.40
Nova Scotia	71	20	8	66	20	14	1.33
New Brunswick	82	15	3	78	16	6	1.40
Quebec	77	18	5	62	28	10	1.35
Ontario	52	22	26	44	25	31	1.19
Manitoba	55	32	13	44	35	21	1.24
Saskatchewan	32	29	39	18	22	60	1.03
Alberta	37	36	27	24	28	48	1.09
British Columbia	65	21	14	55	26	19	1.28
Total	40	30	30	28	26	46	1.10

[a] Residues coverage required (Mg ha^{-1}) = Conventional tillage % × 1.5 Mg ha^{-1} + Conservation tillage % × 1.1 Mg ha^{-1} + No-till % × 0.75 Mg ha^{-1}.

(6–9%) and 1.1–1.7 Mg ha^{-1} for moderate slope (10–16%). Their parameters were considered necessary for controlling water erosion. Other recommended amounts of straw residues required to protect the soil from wind and water erosion range between 30% and 75% [24,25].

In this study, it is assumed that residues left on the land depend on the type of tillage: 1.5 Mg ha^{-1} for conventional tillage, 1.1 Mg ha^{-1} for conservation tillage, and 0.75 Mg ha^{-1} for no-till. The percentages of land under tillage in each Canadian province are obtained from Statistics Canada agricultural census for 2001 and 2006 [26] as shown in Table 2. The term "conventional tillage" refers to tillage incorporating most of the crop residue into the soil; "conservation tillage" refers to tillage retaining most of the crop residue on the surface. Due to lack of annual data, the percentage of land under tillage for each province is determined from the mean of 2001 and 2006 data. The computation of soil conservation per hectare is also presented in Table 2 as residue land coverage. It can be seen that Saskatchewan requires the lowest amount of residue land coverage because of the high percentage of land under no-tillage or zero-tillage.

Fig. 3 presents average available residues per year that can be removed from land and further used for livestock feeding/bedding and other industrial purposes. Total Canadian agricultural residue yield after deducting soil conservation amounts to 54.8 million dry Mg per year compared with total crop residue yield of 82.4 million dry Mg without any deductions. Wheat straw decreased from an average of 37.4 to 27.1 million dry Mg per year. Some grains have a high crop and crop straw yield, such as corn with an average yield of 8.6 Mg ha^{-1} in Ontario. Therefore, available residue per hectare that can be removed from the farm is still high. Other crops have low residue yield, such as canola and flaxseed in Saskatchewan (1.47 and 1.38 Mg ha^{-1} respectively), so their available removable residues are less than 1 Mg ha^{-1}. In practice, residue coverage of more than 1 Mg ha^{-1} may not be applicable to flax because flax straw is difficult to degrade and farms usually bale the straw for removal. Fig. 3 is a theoretical estimation of crop residues which can be removed from land by provinces based on the above assumptions. Precise conservation amounts for given locations can be estimated through specific research on residue retention at much lower levels of disaggregation.

3.3. Straw used for animal feeding and bedding

In estimating Canadian crop residue supply to meet cellulosic ethanol biorefinery feedstock requirements, it is important to recognize further competition for such residues to support the livestock industry, in particular the beef and dairy cattle sector which uses a majority of crop residues (typically baled straw) for animal feeding and bedding. In this study, agricultural residue availability for ethanol conversion is defined as total residue production deducting soil conservation and animal use. There are differences in the amounts used for feeding and bedding; these differences are influenced by several factors, such as climate, weight of animals, animal breed, and farm size. There is a lack of precise data for hay and straw used for feeding and bedding. In the calculation of available cereal straw in Canadian Prairies, Sokhansanj et al. [11] assumed 2.5 kg for bedding and 2.5 kg for straw feeding per head per day for cattle during certain days, based on feeding recommendations of 2.5 kg hay/straw per day from the Ontario Ministry of Agriculture and Food. However, there is no reported data on

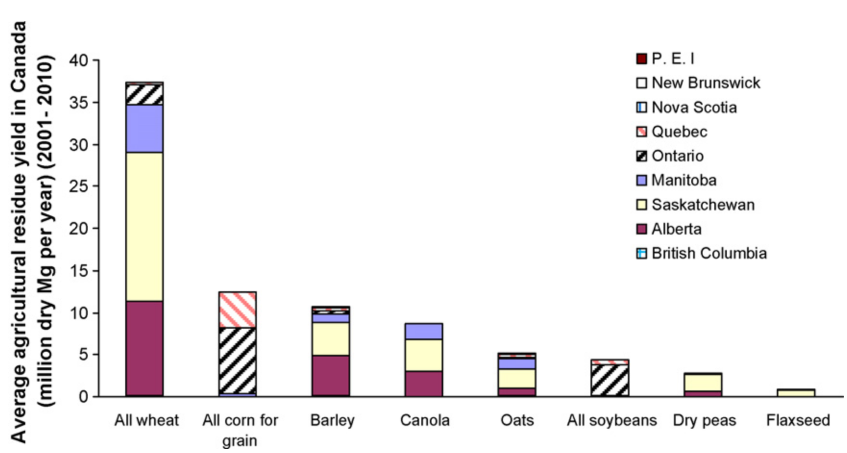

Fig. 2. Average annual Canadian crop residue yield for the period 2001–2010.

Table 3
Estimates of crop residue use for animal feeding and bedding per year[a] (million dry Mg).

	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001
Saskatchewan	1.16	1.24	1.28	1.33	1.35	1.41	1.37	1.25	1.15	1.13
Alberta	2.08	2.19	2.27	2.44	2.41	2.55	2.44	2.34	2.45	2.48
Ontario	0.91	0.95	0.98	1.07	1.10	1.15	1.15	1.13	1.11	1.09
Manitoba	0.73	0.75	0.80	0.84	0.89	0.90	0.89	0.84	0.79	0.75
Quebec	0.87	0.87	0.89	0.90	0.92	0.95	0.97	0.93	0.91	0.91
British Columbia	0.24	0.26	0.27	0.29	0.30	0.33	0.35	0.33	0.31	0.30
P.E.I.	0.10	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04
New Brunswick	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05
Nova Scotia	0.04	0.03	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05
Total	6.14	6.36	6.61	7.00	7.10	7.42	7.31	6.95	6.87	6.80

[a] Crop residue used by livestock = Cattle feeding** + Cattle bedding*** + Pig bedding****.
**Cattle feeding used = number of cattle (h) × 1 kg h^{-1} d^{-1} × 150 d.
***Cattle bedding used = number of cattle (h) × 2 kg h^{-1} d^{-1} × 100 d.
****Pig bedding used = number of pig (p) × 1 kg p^{-1} d^{-1} × 100 d.

hay/straw ratios. For dairy cattle, cereal straw can replace hay when there is a shortage in the supply of good quality hay, slough hay, and cereal hay [27]. In addition, straw is considered to be a good choice due to its availability. However, unlike hay, higher amounts of straw will negatively affect the nutrient density of the ration and may reduce cattle intake; chopped straw feed ration recommendation for dairy cows is between 0.25 and 0.5 kg $head^{-1}$ day^{-1} (kg h^{-1} d^{-1}) [28]. Because Canada produces 25.8 million dry Mg tame hay and 7.8 million dry Mg fodder corn per year for animal feeding, crop straw used as animal feeding is only a small amount. Therefore, this study assumes 1 kg h^{-1} d^{-1} straw for cattle feeding. Estimation of 2 kg h^{-1} d^{-1} for cattle bedding used in this paper is based on Government of Saskatchewan [29] recommendations, namely, 1.4–2.3 kg h^{-1} d^{-1} bedding straw for cows and bred Heifers. Saskatchewan has relatively cold weather, the straw bedding amount for this province will be sufficient for other provinces. Average feeding days of 150 days and bedding days of 100 days for cattle according to Sokhansanj et al. [11] are used in this study.

Besides its uses for beef cattle and dairy cows, straw is also used as bedding for pigs, sheep, and horses. However, other materials such as hay and wood chips are also utilized as bedding. Therefore, it is very difficult to estimate straw consumption for these purposes due to a lack of data. In this paper, besides cattle, only bedding consumption for pigs is calculated. In Canada, pigs are most commonly raised in buildings with concrete without bedding [30]. Hence, the study assumes that the over-estimate from pig straw requirements is sufficient for sheep and horse bedding. Canada has used a hoop structure for pigs for more than 15 years [31]. In this structure, 1 kg straw per pig per day was used for 111 feeding days [32]; similarly, 46 kg for bedding per pig was adapted for 64 days [33]. An average of 100 kg bedding per pig in winter and 55 kg bedding per pig in summer was applied by Honeyman et al. [34]. The hoop structure originated from Canadian Prairies where winters are very cold; hence, straw bedding designed for this structure is assumed to be sufficient for all Canadian regions. This study assumes 100 bedding days and 1 kg of straw per pig per day.

Table 3 presents total agricultural residues needed for animal use (including cattle and pigs). Data on cattle and pig numbers on farm is based on July records derived from Statistics Canada [35–39]. An average of 6.9 million dry Mg of straw is needed for livestock feeding and bedding per year. Alberta has the largest number of cattle. Therefore, it has the highest straw demand for livestock, around 2.4 million dry Mg per year.

3.4. Available crop residues for biofuel conversion in Canada

Table 4 computes the average amount of available agricultural residues per year for cellulosic ethanol production after deducting soil conservation and livestock requirements. A negative number in British Columbia means its agricultural residue supply cannot meet the province's straw demand for soil conservation and livestock use. Therefore, there are no agricultural residues left for cellulosic ethanol production and other processing purposes in British Columbia. Saskatchewan has the highest agricultural

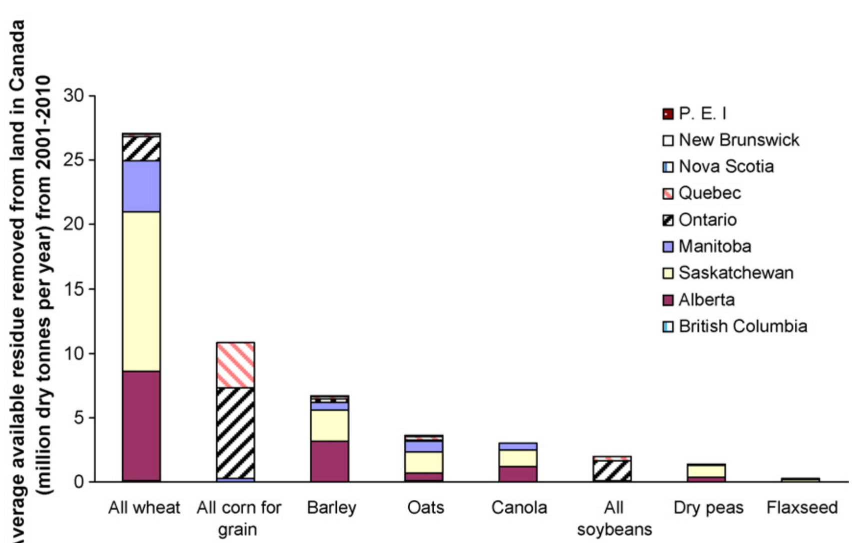

Fig. 3. Average available crop residues removed from land in Canada from 2001 to 2010.

Table 4
Estimate of average agricultural residue availability (million dry Mg) for ethanol conversion in Canada for the period 2001–2010.

	Total crop residue production[a] (million dry Mg yr^{-1})	Total available residue removed from land[b] (million dry Mg yr^{-1})	Total available residue for biofuel[c] (million dry Mg yr^{-1})
Saskatchewan	30.34	18.65	17.38
Alberta	20.65	13.94	11.58
Ontario	14.19	10.78	9.71
Manitoba	10.69	6.57	5.75
Quebec	5.88	4.46	3.55
British Columbia	0.27	0.15	−0.15
P.E.I.	0.18	0.10	0.06
New Brunswick	0.10	0.06	0.02
Nova Scotia	0.05	0.04	<0.01
Total	82.35	54.75	47.90

[a] Total crop residue = SUM of (top eight crop production × straw/grain ratio).
[b] Residue removed from land = SUM of (crop residue yield per hectare − residue remain on land per hectare) × hectares.
[c] Residue available for biomass biofuel = residue removed from land − livestock used.

residue amount estimated at an annual average of 17.38 million dry Mg over the 10-year period. This is followed by Alberta, Ontario, Manitoba, and Quebec with 11.58, 9.71, 5.75, and 3.55 million dry Mg respectively. In terms of percentage contribution to lignocellulosic feedstock supply for cellulosic ethanol production, Saskatchewan accounts for 36% of total available crop residues. Taken together, Canadian Prairie provinces account for 72% of lignocellulosic feedstock supply from agricultural sources. Eastern Canadian provinces of Ontario and Quebec contribute 20% and 3.55% respectively, for a total of about 24%.

3.5. *Crop residue annual availability*

The preceding section presented only average amounts of available crop residues per year. It is useful to present annual variability since crop and residue yield depends on climate conditions. Since estimates of crop residue supply are based on grain yield and straw/grain ratios, the computed residue amounts will also show seasonal variability as a function of climatic conditions. This annual variability in agricultural residue production is depicted in Fig. 4 for the 2001 to 2010 period. It is calculated from grain/straw ratio and crop production data from Statistics Canada [16], without considering soil conservation and livestock use (Fig. 5 accounts for soil conservation and livestock use). Looking at Fig. 4, wheat straw has a 10-year average production of 37.4 million dry Mg, accounting for 45% total Canadian agricultural residues. This is due to the fact that wheat has the largest production and a corresponding high straw/grain ratio. However, wheat straw also has wide inter-season fluctuations ranging from a minimum of 24 million dry Mg to a maximum of 44 million dry Mg per year. Drought years of 2001 and 2002 resulted in the lowest crop and crop residue production on the Prairies. Looking at total residues from all the crops, the minimum production year (2002) generated a total of 53 million dry Mg of residues (27 million dry Mg less than average) while the maximum year (2008) produced 101 million dry Mg.

Fig. 5 depicts annual availability of agricultural residues by province, taking into account soil conservation and livestock uses of crop residues. Hence, this is the residual amount available for ethanol production. Higher crop residue availability in some years compared to others reflects annual variation in crop production and animal numbers. Saskatchewan has the largest supply of crop residues per year because of its high crop production, with potential to supply 17.4 million dry Mg of crop residues per year for biofuel production. Saskatchewan has a maximum supply of 23.1 million dry Mg in 2009 and a minimum of 7.7 million dry Mg in 2002. Alberta has the second largest residue production; however, due to its high livestock population, the demand for crop residues for livestock use is also high. In years when climate is not very favorable for crop production, available residues for cellulosic ethanol production in Alberta would also be influenced dramatically, for example, 2.9 million dry Mg of residues were available in 2002. Crop production is influenced by climatic conditions, local demand, crop variety, and crop rotation [40], especially in large production areas like the Canadian Prairies. For instance, two weather-related

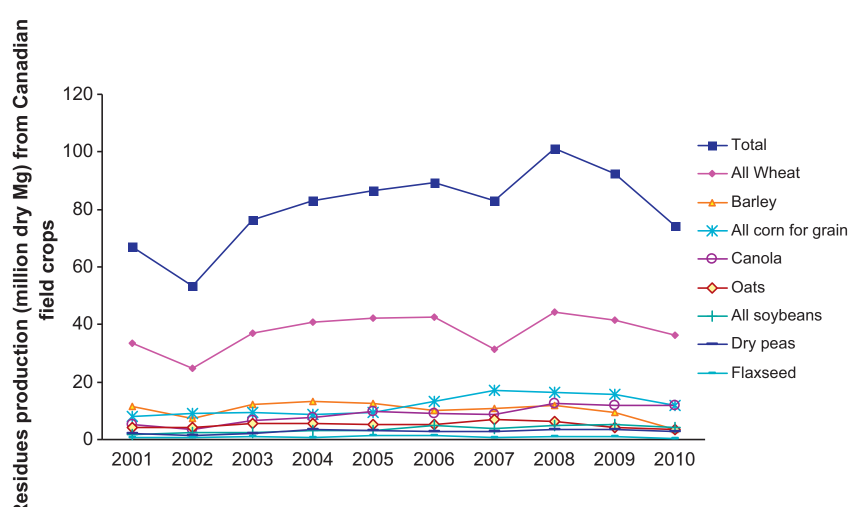

Fig. 4. Annual variation of Canadian crop residue production (2001–2010).

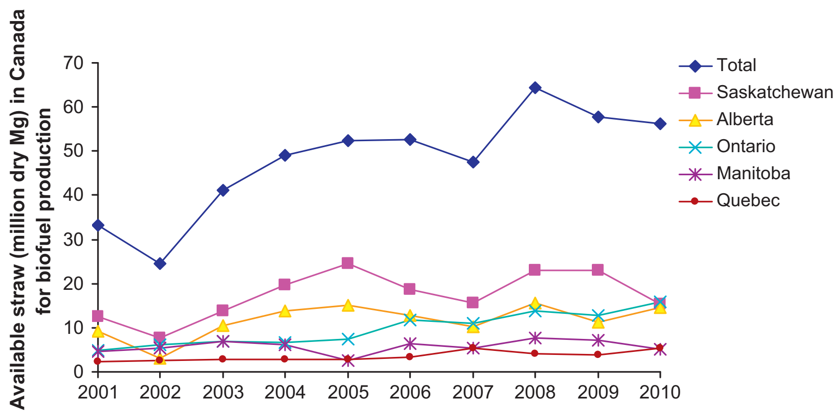

Fig. 5. Availability of crop residues in Canada for ethanol conversion.

events had an impact on yield: the 2001–2002 drought followed by a cold spring; and the excessive rain of 2007. These events influenced crop production significantly in Saskatchewan and Alberta, both major producers of agricultural crop residues. Similarly, Manitoba had a significant decrease in both harvested area and crop production in 2005, with only 2.7 million dry Mg of crop residues available as feedstock for ethanol production. Ontario and Quebec showed relative consistency in their crop residues availability, with 4.7 and 2.2 million dry Mg in their minimum crop production year 2001 respectively. British Columbia, P.E.I, New Brunswick, and Nova Scotia do not have sufficient crop residues for use as cellulosic ethanol feedstock because of their comparatively low crop production. However, some of these provinces, for instance British Columbia, are rich in forestry resources which are potential sources of lignocellulosic biomass feedstock for an ethanol biorefinery.

Beside weather conditions, it is also useful to recognize the role of summerfallow (Fig. 6) in explaining yield trends for the Prairies and hence its potential impact on sustained supply of lignocellulosic biomass feedstocks depicted in Fig. 5. Summerfallow refers to the land that farmers do not cultivate during the growing season to increase soil water reserves and improve the chances of growing a crop in the subsequent season. Only western provinces of Canada (British Columbia, Alberta, Saskatchewan, and Manitoba) have summerfallow each year [16]. Summerfallow is a primary rotation practice especially in the drier or more arid production regions of western Canada. In general, the adoption of conservation tillage has led to gradual reductions in summerfallow, as shown in Fig. 6. However, this figure also shows that summerfallow in 2010 increased in Saskatchewan to its highest level since 2001, mainly as a result of flooding in many regions during the 2010 planting season. In Saskatchewan, 3.72 million hectares of summerfallow were reported in 2010, an increase of 124% compared with 1.66 million hectares in 2009. Manitoba reported 287,000 ha, an increase of 50% from 192,000 ha in 2009. This can explain why available crop residues dropped in 2010 in Saskatchewan and Manitoba. Alberta shows a continuous downward summerfallow trend over the 10-year period. A possible consequence of the rapid increase in grain and oilseed production in Saskatchewan is the potential shift of economically marginal land to grain and oilseed production, a factor that could further contribute to the overall increase in summerfallow in certain years. On the other hand, Alberta, which has higher moisture and hence tends to have more continuous cropping, exhibits continuous decreases in summerfallow. Moisture deficits represent a greater constraint in Saskatchewan, hence its higher adoption rate of conversation tillage practices compared to Alberta, as Table 2 above clearly shows. Although a detailed empirical quantification of summerfallow is beyond the scope of this paper, it is worth simply noting the role of summerfallow as a factor in the estimation of future agricultural crop residue supply. This is a topic for future research.

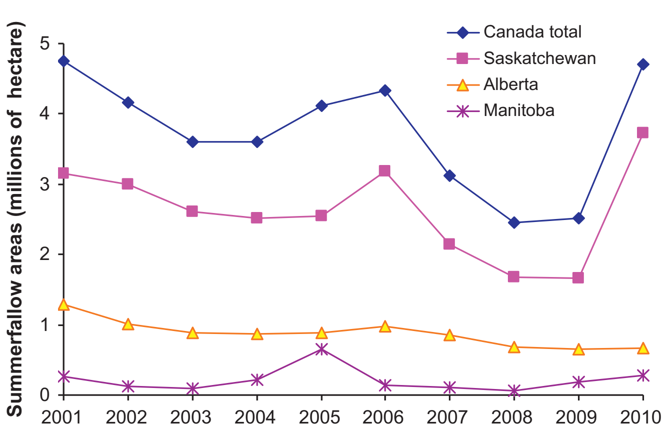

Fig. 6. Summerfallow trends in Western Canada (2001–2010).

3.6. Crop residue yield per hectare by province

It is interesting to examine provincial crop residue yield per hectare over the 10-year period, as summarized in Table 5 based on Statistics Canada data [16]. Ontario has the highest crop residue yield per hectare for most crops while Saskatchewan has the lowest. However, Saskatchewan has the highest quantity of crop residues compared to all other provinces given that it has the highest cultivated area. Saskatchewan harvested areas for winter wheat, spring wheat, and durum wheat in 2010 are 0.07, 2.85, and 1.10 million hectares respectively while in Ontario they are 0.33, 0.05, and 0 million hectares respectively. Looking at the long term yield trends, Saskatchewan data does not show a significant increase in crop yield in the last 10 years, while Ontario has an upward trend mainly due to yield increases of more than 30% from corn and soybean between 2001 and 2010.

3.7. Crop residue yield variation by soil zone

In terms of long term supply of cellulosic biomass as it relates sustainability of land, it is useful to describe yield trends in specific soil zones where the majority of crop residues targeted for cellulosic ethanol production would originate. As noted earlier, Canadian Prairies account for 72% of total Canadian agricultural residue supply. The Prairies are classified into five main soil zones which are closely related to climatic and productions patterns, namely Black, Brown, Dark Brown, and Dark Gray Chernozems,

Table 5
Average crop residue yield (Mg ha^{-1}) from 2001 to 2010.

Crop residues	Crop residues yield (Mg ha^{-1}) in province								
	PE	NB	NS	QC	ON	MB	SK	AB	BC
Winter wheat straw	3.58	3.90	4.72	3.65	6.06	4.62	3.05	3.78	–
Spring wheat straw	4.74	4.58	4.93	4.85	5.42	4.27	3.36	4.45	3.97
Durum wheat straw	–	–	–	–	–	3.75	3.39	4.20	–
Barley straw	2.91	3.13	2.92	3.05	3.32	3.22	2.62	3.18	2.74
Corn stover	–	4.44	7.08	8.00	8.58	5.99	–	6.07	–
Canola straw	–	–	–	2.09	2.06	1.73	1.47	1.78	1.47
Oats straw	3.87	3.81	3.65	3.75	3.87	4.28	3.59	3.90	3.78
Soybean straw	2.24	–	–	2.59	2.53	1.84	–	–	–
Peas straw	–	–	–	–	–	2.40	1.92	2.30	2.12
Flax straw	–	–	–	–	–	1.54	1.38	1.91	–

and small forest areas of Gray Luvisol as shown in Fig. 7 [41]. The Black soil zone is the most fertile with comparably more precipitation (approximately 4100 mm) and a frost-free period generally exceeding 100 days. The Brown and Dark Brown soil zones are characterized by low precipitation as a factor affecting crop production while the Gray zone has low natural soil fertility and a very short frost-free period, typically less than 80 days.

Saskatchewan has a clear soil zone distribution with a good time series of data that can be readily linked to each soil zone, using Crop Reporting District data, as shown in Fig. 8 [42,43]. Hence in this section, Saskatchewan was used as a case study to analyze crop residue availability by soil zone, coupled with the fact that this province also accounts for the largest proportion of agricultural crop and crop residue production in Canada. The analysis used 10 years of data collected by Saskatchewan Ministry of Agriculture from 296 rural municipalities as shown in Fig. 8 [42,43].

The results are presented in Fig. 9 and show that the Brown soil zone has the lowest crop residue yields, followed by the Dark Brown soil zone. The Black, Dark Gray, and Gray soil zones have relatively high crop and crop residue yields. This is because the Black soil has high organic matter content and hence higher fertility, whereas the Brown soil zone tends to have lower fertility because of lower organic matter content.

Approximately 6.3, 7.28, and 7.52 million hectares of land in Saskatchewan are Brown, Dark Brown, and Black soil zone, out of which 69%, 82%, and 73%, is cultivated, respectively [41]. Only 45% of the land in the Dark Gray and Gray soil zones is cultivated; in particular, the Gray soil zone is dominated only by four to five rural municipalities. Fig. 10 presents annual crop residue yield trends for the four dominant soil zones of Saskatchewan.

A slightly increasing trend for crop residue yield can be observed for most of the crops. However, yearly variation and the seasonal impact of weather and other factors affecting yield are obvious from the undulating trend. Oats straw has the highest residue yield across all soil zones as depicted in Fig. 10. However, oats account only for a small fraction of total grain production and harvested areas, with wheat retaining its dominance in supplying residues as feedstocks for cellulosic ethanol production in Saskatchewan. The

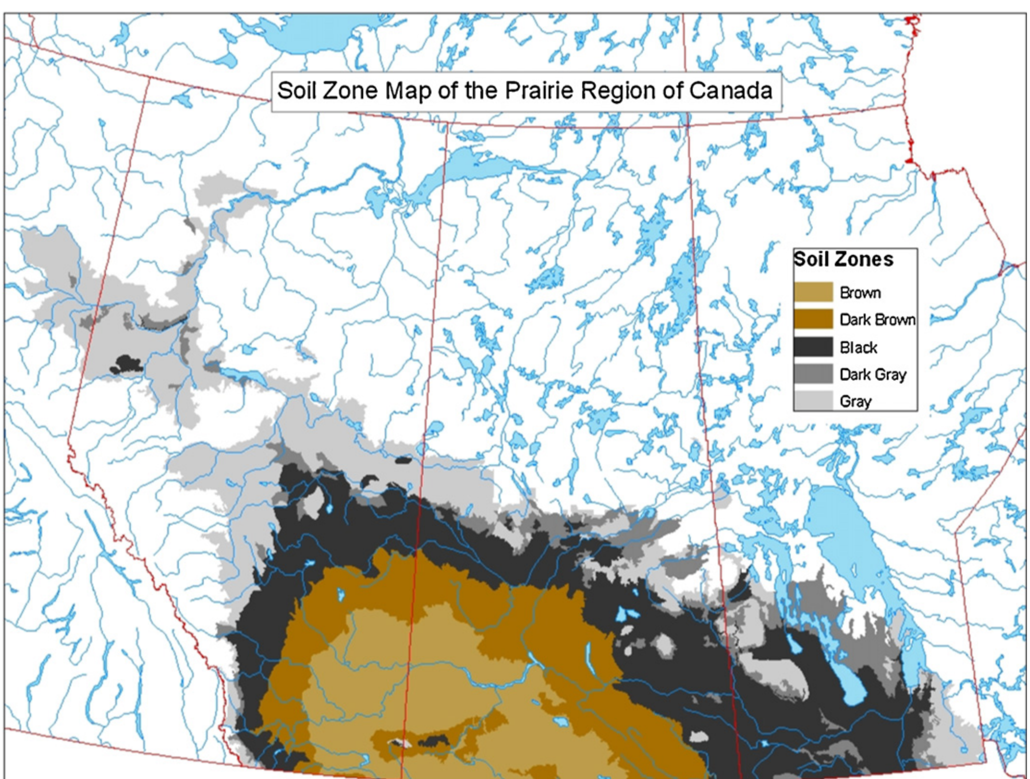

Fig. 7. Soil zones of the Canadian Prairies.

Agriculture and Agri-Food Canada.

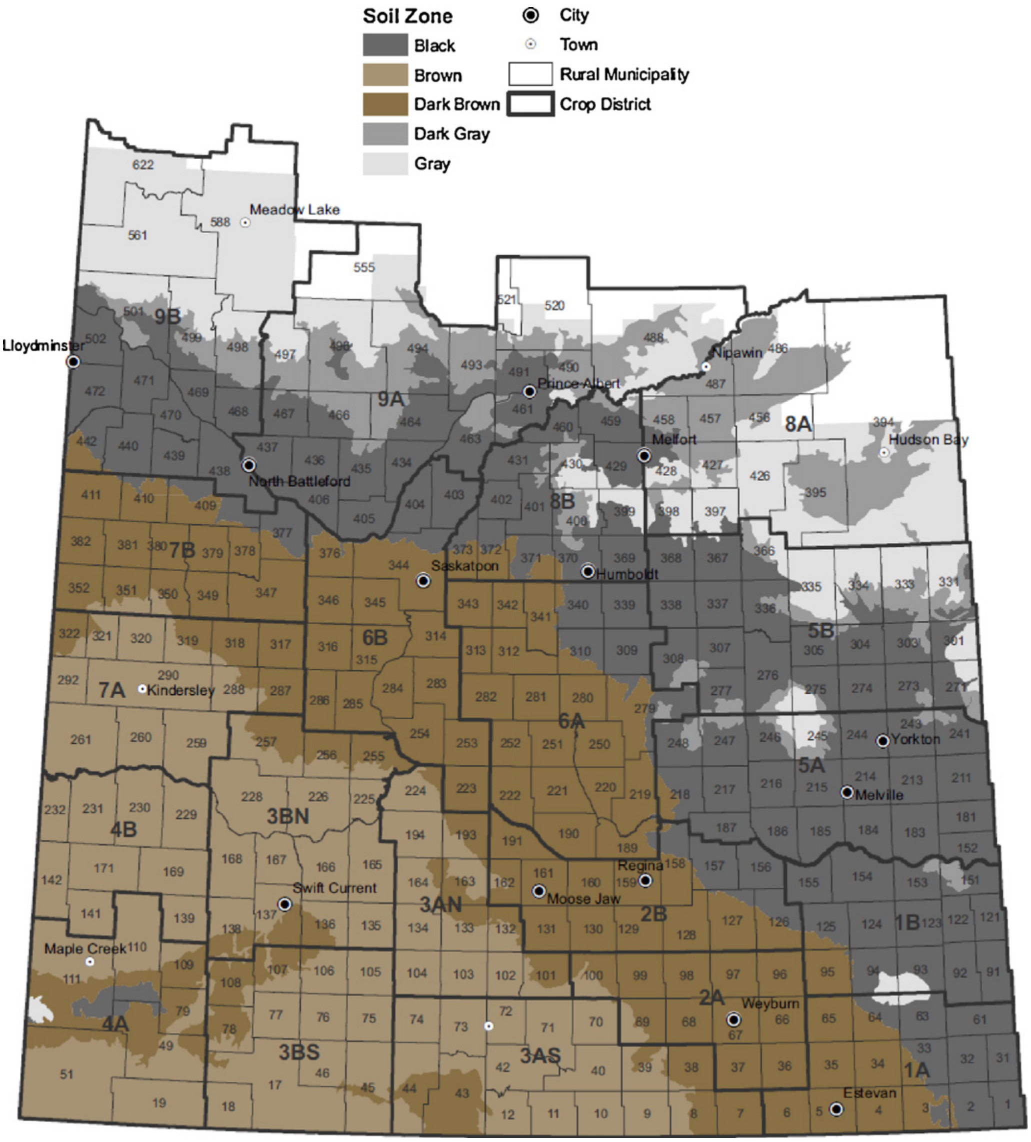

Fig. 8. Saskatchewan soil zones, crop reporting districts, and rural municipalities.

Saskatchewan Ministry of Agriculture.

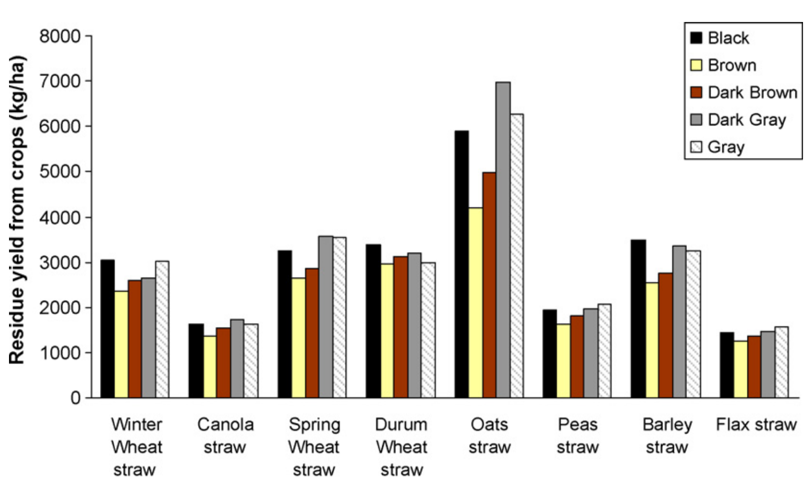

Fig. 9. Average crop residue yield by soil zone in Saskatchewan 2001–2010.

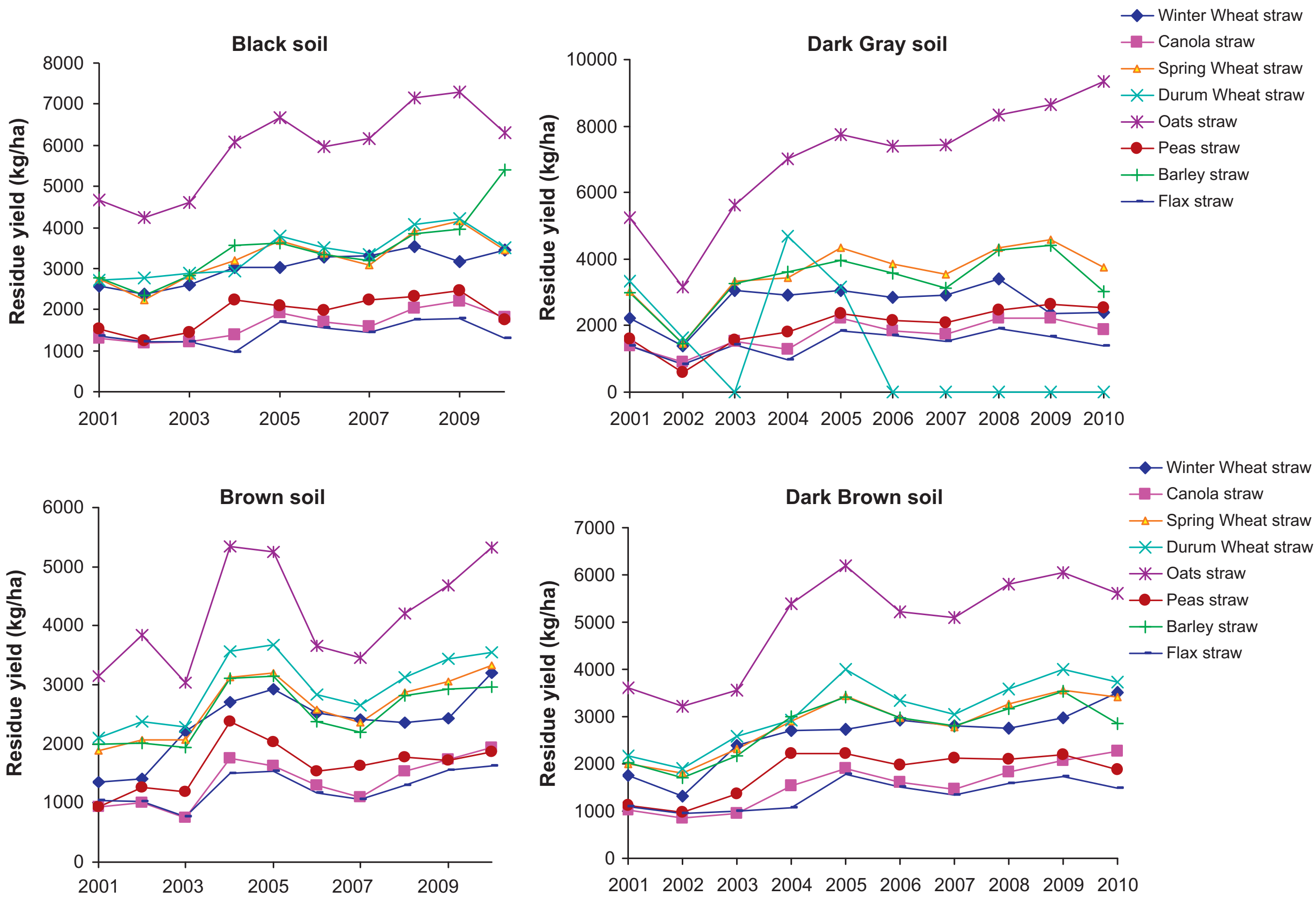

Fig. 10. Crop residue yield vs. soil type in Saskatchewan.

small volume and scattered nature of oat production would impose high costs on the logistics of collecting oat biomass and require integrated utilization with other straw sources such as wheat which has the largest cultivated area and second highest per hectare biomass yield. A further examination of Fig. 10 shows that the Black and Dark Brown zones have the highest straw yields. Analyzing production over this longer period and by soil zones enables one to depict the impact of seasonal variability and location-specific oscillation in production.

Starting from September 2010, a federal mandate of five percent ethanol blend into gasoline was implemented in Canada. Prior to this period, Manitoba and Saskatchewan already required 8.8% and 7.5% ethanol blends [44]. Ontario produces nearly 50% of Canada's ethanol, followed by Saskatchewan, Manitoba, Quebec, and Alberta. Canadian ethanol is mainly from wheat (Western Canada) and corn (Eastern Canada). In 2009, 69% domestic ethanol was made from corn, 30% from wheat and 1% from other feedstocks such as wood waste and wheat straw [45]. Ethanol demand in Canada keeps increasing yearly and estimated consumption is expected to rise to 2.2–4 billion litres in 2011, exceeding 2010 Canadian ethanol capacity of 1.9 billion [15,46]. Currently only Iogen (Ottawa, Ontario) and Enerkem (Westbury, Quebec) have plants designed to use cellulosic feedstocks (wheat straw and wood waste, respectively) to produce ethanol in Canada. Their respective annual capacities currently are 2 million and 5 million litres, clearly indicating that there is significant scope for expansion given current lignocellulosic feedstock supply from agricultural residues.

Unlike starch based ethanol production, ethanol made from lignocellulosic materials is more complex. Theoretical conversion rates from lignocellulose to ethanol cannot be applied because of the complexity of lignocellulosic matrix and processing. Ethanol production from lignocellulosic biomass will require pretreatment, hydrolysis, fermentation, and distillation. Barriers to cellulosic bioethanol are biomass transportation, lower sugar yield, and inhibition during hydrolysis and fermentation. Most reported estimated commercial conversion rates from agricultural residues are from corn stover, and range from 320 to 340 litres per dry Mg biomass [47,48]. Mabee and Saddler [9] reported lower ethanol conversion and yield rates from lignocellulosic biomass ranging between 110 and 270 l per dry Mg. An ethanol conversion rate of 270 l per dry Mg biomass is used in this study to estimate potential ethanol production from Canadian agricultural residues.

Fig. 11 presents estimated potential Canadian ethanol production from available agricultural residues by province, assuming a conversion rate of 270 l of ethanol from 1 dry Mg of straw. Saskatchewan, Alberta, Ontario, Manitoba, and Quebec all have high potential for ethanol production from crop residues, averaging close to 1 billion litres annually over the 2001 to 2010 period. Other provinces are not presented here either because their potential production is less than 20 million litres per year or they do not have enough agricultural residues in certain years to supply an ethanol plant. Total Canadian potential is 12.95 billion litres per year on average from 2001 to 2010 with 6.6 billion litres in the minimum year 2002, which still exceeds both the 1.9 billion litres total ethanol capacity of 2010 and the federal government mandate of 5% renewable fuel content [44]. The expected ethanol consumption in 2036 is 3.7 billion litres [46]. Maximum and minimum production possibilities are presented in Fig. 11 and demonstrate annual variation in agricultural residue availability. Although climate conditions have a significant impact on crop yield, all the five provinces still have

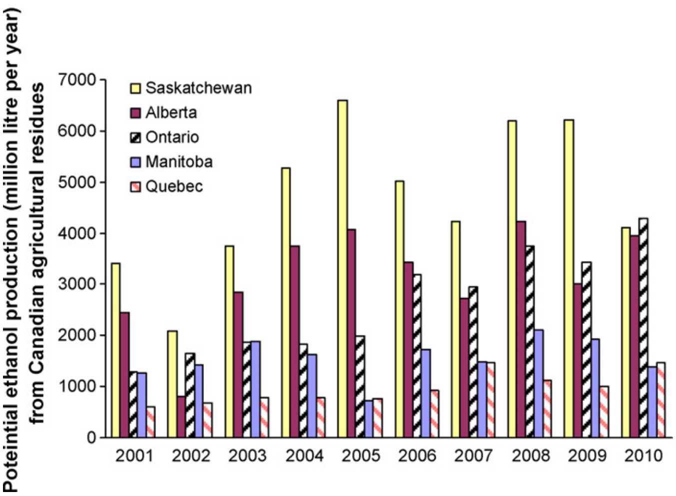

Fig. 11. Potential ethanol production from agricultural residues in Canada.

potential to produce more than 500 million litres of ethanol per year from crop residues even in their minimum crop production year based on this 10-year period. This production potential is much higher than current capacity available at existing ethanol plants such as Iogen and Enerkem (with 2–5 million litres yr^{-1} capacity), and represents a commercial production gap and basis for each province to set up several cellulosic ethanol plants without the risk of inadequate agricultural residue supply.

Transportation of biomass has inherent logistical barriers that limit the size and scale economies of ethanol production plants because of high demand and low density of biomass. Therefore, the selection of ethanol plant location is very important in minimizing transportation cost. This study shows there is enough resource to produce ethanol from crop residues in five provinces. The transportation costs, which generally increase linearly with distance, would be better contained in regions with high density biomass availability coupled with location of ethanol biorefinery plant in regions of high biomass concentration. In this respect, ethanol plants could be in Saskatchewan, Manitoba, south eastern Alberta and Ontario, and eastern Quebec. This can also be inferred from AAFC's BIMAT [13]. For instance, the distribution of soil zones depicted in Fig. 7 [41] shows that Manitoba is rich on Black and Dark Gray soil types, which would correspond to higher crop residue yields and hence save transportation costs if a cellulosic biofuel plant is established close to these high residue yield regions.

4. Conclusion

This study provides new estimates of lignocellulosic biomass availability from Canadian agricultural crop residues for the period 2001–2010, including potential cellulosic ethanol production capacity by province. The analysis showed significant variability in the supply of agricultural crop residues over the 10-year period. On average, about 82.4 million dry Mg of agricultural residues were produced in Canada, dominated by wheat straw. Total Canadian agricultural residue yield after deducting soil conservation amounts to 54.8 million dry Mg per year. A further 6.9 million dry Mg of straw is needed for livestock feeding and bedding per year, leaving an estimated 47.9 million dry Mg available for cellulosic ethanol production, with a minimum of 24.5 million dry Mg available in the lowest crop yield year. Saskatchewan has the highest agricultural residue amount estimated at an annual average of 17.38 million dry Mg over the 10-year period. This is followed by Alberta, Ontario, Manitoba, and Quebec with 11.58, 9.71, 5.75, and 3.55 million dry Mg respectively. In terms of percentage contribution to cellulosic feedstock supply, the prairie provinces account for 72% of cellulosic feedstock supply from agricultural sources. The Eastern Canada provinces of Ontario and Quebec contribute 20% and 3.55% respectively. The estimated 48 million dry Mg of crop residues (and its estimated minimum of 24.5 million dry Mg) can generate an average of 12.95 billion litres (and a minimum of 6.6 billion litres) of ethanol annually. Understanding variability in feedstock supply is important for planning biorefinery operations. Climate and summerfallow are important factors in influencing crop production and hence biomass supply in the Canadian Prairies. Year-to-year production in Saskatchewan and Alberta is more dependent on climate than Ontario, as evidenced by drought years of 2001–2002 which had an adverse impact on crop yields in Saskatchewan and Alberta. This study also examines biomass supply and its variability at soil zone level using Saskatchewan as a case study based on the fact that this province accounts for 36% of total available crop residues in Canada.

Factors such as residue yield per hectare and soil zone will influence cellulosic ethanol plant establishment because of the need to exploit abundance of local lignocellulosic feedstocks. In addition to quantifying the availability agricultural residues, this paper provides scope for biorefinery managers to manage the timing of feedstock supply, including implications for collecting, transporting, and storing. For those provinces whose potential ethanol production is less than 20 million litres per year or whose agricultural residue supply is deficient in certain years, there is further need to analyze alternative sources of lignocellulosic biomass such as forestry residues. Overall, Canadian potential ethanol production over the 2001–2010 period is 12.95 billion litres per year (with 6.6 billion litres in the minimum year), exceeding the current Canadian ethanol capacity and providing sufficient lignocellulose to support Canadian ethanol consumption in next decade based on legislated mandates.

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